IMPROVING AND UNDERSTANDING kWh/kWp SIMULATIONS

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ABSTRACT:
Discrepancies have been found between the models used in PV simulation programs and outdoor measurements. 3rd party PV kWh/kWp measurement reports sometimes show insufficient data to understand their results and often make incorrect assumptions as to the cause and importance of the results (which often differ in ranking).

Suggestions are made on how to improve the modelling of PV arrays and comparisons with measured data.

A new “Loss Factors Model” has been developed with Oerlikon Solar which can model outdoor IV curves for different PV technologies at different sites under different weather conditions.

Keywords: Energy performance, Modelling, System performance, Energy rating

1 INTRODUCTION
Independent comparisons of kWh/kWp from different technologies often find values of kWh/kWp within experimental error of each other and much less variability than some manufacturers’ claims[1][2][3][4]. Discrepancies have previously been found between the 1-diode models used in several commercial PV simulation programs (PVSP) and measured outdoor performance [5][6] - differences have been found in their assumptions of RSHUNT as a function of irradiance (this is not on the manufacturers’ datasheets [7] and will vary for each module type).

Modules are also graded in manufacture into finite width bins (e.g. ±2Wp) and the distribution of modules within these bins must be taken into account in modelling.

2 SIMULATION PROGRAM IV CURVE DISCREPANCIES

Figures 1 and 2 show predicted IV curves at both 1000 and 200W/m² for a commercial Thin Film and a c-Si module respectively [6] from four different PVSPs.

Grey lines plot the ISC, VOC, ISMP and VMPM from the manufacturer’s datasheets at 1000W/m² and 200W/m² scaled by irradiance, black curves give the lines of constant PMAX at 1000W/m² and the manufacturers’ measured values at 200W/m².

Modelled ISC and VOC values differ at 1000W/m² although the programs predict the ISMP and VMPM similarly at 1000W/m². At 200W/m² they all predict similar ISC but the curves near VMP and VOC are very different. The RSHUNT for c-Si are modelled differently. PMAX at 200W/m² for program Z is much higher than program X.

Figure 3 shows the PVSP predicted IV curves and PMAX points (brown dotted line) with irradiance (200 to 1000W/m²) for the thin film module in Figure 1. The RSC value vs. Irradiance (black line upper x, right y axes) shows more than a 2:1 variation between the highest (X) and lowest (Z) model. Measurements of RSC vs. G1 were performed outdoors by Oerlikon Solar on micromorph [6] and indoors by BP Solar on c-Si [6] confirming similar approximate shapes of the RSC vs. G1 curve but the magnitude will be module and technology dependent and in PVSPs is just guessed value.

These discrepancies between the modelled IV curves under different irradiances and temperatures dominate the kWh/kWp predicted by different PVSPs.

3 ELECTRICAL VARIABILITIES ON MANUFACTURER DATA SHEETS

PVSPs programs assume the modelled performance will be due to values from just one IV curve from their model without any allowances for module variability and uncertainty.

There will be site dependent variability (microclimate, yearly weather variation) plus uncertainties in both the calibration module and the manufacturer’s flash tester [6].

Module manufacturers very rarely produce publically available data for the expected variability in performance between all modules in one bin (for example 200-210Wp) but a minimum estimate of the uncertainty can be taken from the datasheet values of ISC, ISMP, VMPM, FF and VOC per PMAX bin.

Figures 4 and 5 show a manufacturer’s defined values
increase over the lowest $P_{\text{MAX}}$ bin on the sheet. As $P_{\text{MAX}} = I_{\text{MP}} \cdot V_{\text{MP}} = I_{\text{SC}} \cdot V_{\text{OC}} \cdot F_{\text{FF}}$ then stacked bar graphs of $\Delta I_{\text{SC}} + \Delta V_{\text{OC}} + \Delta F_{\text{FF}}$ and $\Delta I_{\text{MP}} + \Delta V_{\text{MP}}$ will show the proportion of improvement in $P_{\text{MAX}}$ due to each of these parameters.

Figure 4 shows the proportion of improvement from a c-Si cell manufacturer with approximately 2.4% $P_{\text{MAX}}$ bin widths. This graph (which may not apply to all c-Si) shows that approximately 1/3 of the improvement is due to each of $I_{\text{SC}}$, $F_{\text{FF}}$ and $V_{\text{OC}}$ and slightly more due to $V_{\text{MP}}$ than $I_{\text{MP}}$. This means that for each 2.4% wide $P_{\text{MAX}}$ bin there must be at the very least 0.8% variation due to $I_{\text{SC}}$, $F_{\text{FF}}$ and $V_{\text{OC}}$ and about 1.3% due to $V_{\text{MP}}$ and 1.1% due to $I_{\text{MP}}$ differences.

Figure 5 shows values for a CdTe manufacturer (which may not be the same for all CdTe or thin film). Here the $P_{\text{MAX}}$ bins are >4% apart and there is very little improvement in $I_{\text{SC}}$, mostly it is due to $F_{\text{FF}}$ and $V_{\text{MP}}$ more than $V_{\text{OC}}$ or $I_{\text{MP}}$ (indicating that the parameter which determines the $P_{\text{MAX}}$ is likely to be $R_S$ which affects $V_{\text{MP}}$ and $F_{\text{FF}}$ more than others). Over half of the $P_{\text{MAX}}$ change is then due to $F_{\text{FF}}$ and two thirds due to $V_{\text{MP}}$. This means that at the very least there will be something like 2.5% $V_{\text{MP}}$ and 3% $F_{\text{FF}}$ variation between bins.

![Figure 4: c-Si bin values from manufacturer’s datasheet](image)

![Figure 5: CdTe bin values from manufacturer’s datasheet](image)

However these are absolute minima and would only apply if there was perfect correlation between parameters. In reality there are likely to be (higher $I_{\text{SC}}$, lower $V_{\text{OC}}$) and (lower $I_{\text{SC}}$, higher $V_{\text{OC}}$) modules in the same $P_{\text{MAX}}$ bins so the expected distributions of each parameter will be higher.

Purchasers of large numbers of modules from the same $P_{\text{MAX}}$ bin with lists of measured IV curve values can calculate how much higher these are.

4 A NEW PV “LOSS FACTORS MODEL”

Several 3rd party PVSP models have too many non independent modelling parameters, which may be unphysical and/or not normalised making comparisons and results harder to understand.

A new “Loss Factors Model” (LFM) has been developed [8] to study the performance of different technologies by looking at their outdoor IV curves as represented in figure 6 at different sites.

Five different loss factors and two corrections in the LFM were chosen such that they are all independent and the performance factor <001> is the product of all of the loss factors <002>.

$$PF = PR_{\text{DC}} = \frac{\text{dc measured}}{\text{dc nameplate}}$$

$$PF = n_{\text{SC, G}} \cdot n_{\text{SC}} \cdot n_{\text{FF, R}} \cdot n_{\text{OC, T}}$$

where $n_{\text{SC, G}} = (\text{MMF} \cdot n_{\text{SC}})$ and $n_{\text{OC, T}} = (T_{\text{CORR}} \cdot n_{\text{OC}})$.

These are illustrated in figure 6 and are explained further in table 1.

![Figure 6: Identifying the 7 independent normalised coefficients that determine the performance factor in the LFM](image)

**Table 1: Definitions and calculations for the LFM**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{FF}}$</td>
<td>reference Fill Factor $= (r_{\text{MMF}} \cdot r_{\text{VOC}}) / (r_{\text{SC, R}} \cdot r_{\text{VOC}})$</td>
</tr>
<tr>
<td>$T_{\text{CORR}}$</td>
<td>Voltage temperature correction $= (1 + n_{\text{VOC}} \cdot (25 - \text{TMOD}))$</td>
</tr>
</tbody>
</table>

**Normalised loss factors**

$$n_{\text{SC, G}} = n_{\text{SC}} \cdot (I_{\text{SC}} \text{ loss (spectrally corrected)}) \cdot (r_{\text{SC}} / G_{\text{STC}} \cdot F_{\text{FF}})$$

$$n_{\text{SC}} = n_{\text{SC}} \cdot (I_{\text{SC}} \text{ loss}) \cdot (r_{\text{SC}})$$

$$n_{\text{FF, R}} = n_{\text{FF, R}} \cdot (F_{\text{FF}} \text{ loss}) \cdot (r_{\text{FF}})$$

$$n_{\text{OC, T}} = n_{\text{OC, T}} \cdot (V_{\text{OC}} \text{ loss}) \cdot (r_{\text{OC}})$$

**Resultant performance factor**

$$PF = \text{dc measured/STC efficiency} = m_{\text{FF}} / r_{\text{EFF}}$$

$$PF = n_{\text{SC, G}} \cdot n_{\text{SC}} \cdot n_{\text{FF, R}} \cdot n_{\text{OC, T}}$$

**IV curvature checks on shape**

$I_{\text{C}} = I$ curvature factor $= I_2 / I_1 @ V_{\text{MP}} / 2$

$V_{\text{C}} = V$ curvature factor $= V_2 / V_1 @ I_{\text{MP}} / 2$

The “curvature factors” $I_{\text{C}}$ and $V_{\text{C}}$ are useful in checking whether there are losses due to non ideal curves from cell mismatch, breakages or schottky back contacts.

For most well behaved modules tested so far (i.e. without appreciable cell mismatch and Schottky back contacts) these come out to be $100\pm2\%$ whereas deviations outside this narrow range indicates problems and/or degradation.
When fitting LFM coefficients to measured data it has been found useful to divide measurements into several weather types as shown in figure 7. This differentiates the performance under diffuse or clear sky conditions so that separate Angle of Incidence and Beam Fraction coefficients do not need to be added to the seven coefficients above [9].

Clear skies are defined as “when the clearness index $k_{Th} > 0.5$”, morning/evening are separated from noon when the time is $\pm 3$ hours from solar noon.

Low light levels can occur either during “clear mornings or evenings (with high AOL, high beam fraction, low sun height and redder skies)” or “diffuse noons (low beam fraction and bluer skies)”.

The LFM diffuse fits differ from the clear sky fits particularly when the irradiance sensor differs from the PV technology (for example when using a pyranometer). Figure 8 shows how well the loss factors model fits the 5 different parameters for two similar a-Si:uc-Si modules at two Oerlikon Solar Outdoor test facilities (OTF) in very different climates - Arizona (OTF4-AZ left) and Switzerland (OTF1-CH right). The shapes and values of the curves are almost identical apart from the low light $n_{GC,CO}$ which depends on the differences between the spectral and angle of incidence responses between the PV and the irradiance sensors.

Figure 9 shows the temperature and spectrum corrected energy yield measured vs. predicted for a c-Si module in Arizona. The top traces (right axis) show the 5 minute energy yields ($\frac{W_{\text{MEASURED}}}{W_{\text{NOMINAL}}}$) for 6 days in April, the first two are variable diffuse weather and the right 4 are clear sky.

The bottom traces show the module mismatch factor (here it is 0 because the reference cell and module are both c-Si) and the percentage error of the yield, mostly $<\pm 2\%$ apart from the diffuse sky days when the weather was changing erratically.

Figure 10 plots 4 traces for an a-Si:uc-Si module in Arizona. The left column are not temperature corrected, the right hand column are. The top row aren’t spectrally corrected, the bottom row are.

Note the best fit ($<1\%$) for the a-Si:uc-Si module when both corrections are on for the clear sky days, the diffuse days are still a few % out – this may be due to erratic weather causing temperatures to fluctuate and will be checked in steady diffuse conditions.

These are only initial energy yield simulations with the current status of the model which will be further enhanced for even better correlation with measured performance soon.

Figure 9: Energy yield LFM fits to a c-Si module at OTF4-AZ right

Figure 10: Energy yield LFM fits to an a-Si:uc-Si module at OTF4-AZ – temperature correction (left=no, right=yes); spectral correction (upper=no, lower = yes)

5 BETTER REPORTING IS NEEDED

Many 3rd party comparative energy yield studies worldwide only quote the total derived kWh produced by the modules over the year. This sum does not show how
the results are affected due to any errors such as
- poor measurements
- incorrect setup (perhaps inverter matching)
- shading on some or all modules
- poor $V_{mp}$ tracking
- atypical modules (e.g. shunted or cracked cells)
- corrections for missing or poor data
- inverter and BOS losses
- other yield affecting problems.

Listed below are many factors that should be taken into account when reporting measurement and modelling data.

**Simple graphs to prove PV performance claims**

Manufacturers often make claims for extra energy yield for their products vs. their competitors for several reasons but rarely do they show enough monitored data which is easy to represent in the graphs identified below in table 2.

**Table 2: Types of improved performance claimed by manufacturers and graphs they should use to prove or disprove the claim.**

<table>
<thead>
<tr>
<th>Claimed better performance at</th>
<th>Graph to show</th>
</tr>
</thead>
<tbody>
<tr>
<td>low light levels due to</td>
<td>PF vs. $G_i$</td>
</tr>
<tr>
<td>- good $R_{SHUNT}$</td>
<td>- and IV vs. irradiance</td>
</tr>
<tr>
<td>- good diffuse spectrum</td>
<td>- and diffuse fraction</td>
</tr>
<tr>
<td>high light levels due to</td>
<td>PF vs. $G_i$</td>
</tr>
<tr>
<td>- low $I^2R$ loss</td>
<td>- and IV showing $R_{SERIES}$</td>
</tr>
<tr>
<td>- blue spectrum</td>
<td>- and APE</td>
</tr>
<tr>
<td>high temperatures</td>
<td>PF vs. $T_{module}$</td>
</tr>
</tbody>
</table>

**Weather correlations need to be corrected for**

All weather parameters are correlated with each other (high irradiance tends to occur with high temperatures, in summer with low AOI and under clear blue skies etc.).

Figures 11 and 12 show the correlation of weather parameters. Each of the 8 axes of the graph represent a different parameter, normalised and scaled so that a value identified with a high irradiance appears at the outside of the graph and that associated with a low irradiance towards the inside. Correlation between weather parameters is seen when there are many almost parallel lines between the axes, few crossovers or scatter.

Three of the weather types from figure 7 are shown, clear noon, clear evening and diffuse (clear morning isn’t shown for clarity but it’s similar to clear morning with a little higher temperature). ~30 random measurements in April are plotted for each type. The clear noon and clear evening show high $T_{module}$, $T_{ambient}$ and Beam Fraction plus low AOI are associated with high irradiance at both sites. The clear evening shows lower temperatures and beam fractions plus higher AOI than the clear noon.

The diffuse measurements show lower temperatures, varied AOI, higher blue fraction and very low beam fractions than the clear conditions.

When calculating outdoor temperature coefficients for spectrally sensitive devices such as a-Si or CdTe (which absorb more in the bluer end of the spectrum than irradiance sensors of c-Si or pyranometers) these correlations are important.

Because module temperatures tend to be higher under blue skies, the spectrum needs to be corrected for otherwise wrong temperature coefficients are found. Also seasonal annealing gives higher performance after hotter weather so for longer term studies the effect is greater.

**Uncertainty limits on measured side by side comparisons**

Modules of different technologies are measured under the same conditions over a year – then the total sums of kWh/kWp compared. Sometimes modules are measured on their own flash testers and the kWh divided by the kWp flash tested rather than use the manufacturer’s nominal ratings.

Modules are then ranked from highest to lowest kWh/kWp but the uncertainty of the flash test measurements (usually $\pm 2.5\%$ even from test houses to international standards) is often ignored.

kWh/kWp variations of $<5\%$ from best to worst aren’t statistically significant.

Simulation programs will predict one IV curve per time period (usually hourly) i.e. irradiance, temperature and any other modelled input. However as the input values for $I_{sc}$, $P_{max}$ and FF are known to vary as in figure 4 and 5 then allowance for these variations should be made.
User defined input uncertainty

At a 2010 workshop at Sandia in Albuquerque Stein [10] analysed the results from many designers using a variety of different commercial and internal simulation programs to model the same systems and found: -

- Large variation seen in model results
- Variation not entirely consistent across systems
- Uncertainty in assigning derates
- Discomfort when components are not included in database.

Closest fit - modelled vs. measured kWh/kWp studies

Table 3 discusses a hypothetical study where a user models a system that measured 1000kWh/kWp with 4 different simulation programs A-D with default derates as in row 1. Simulation program D would appear to give an exact fit. Now suppose that the dirt derate had to be raised by 2% - the apparent modelled output would fall 2% for each program as in row 2 and model C would now be the best match. Suppose the customer found the average P_{MAX} of the modules supplied was at the low end of the bin at 2% below average then the predictions would fall another 2% as in row 3. It might be that the shading wasn’t allowed for and including a 2% value would result in another fall in row 4.

There is obviously a limit in the number and amount of additions to the nominal derates before the designed output falls to substandard levels but it shows that the “best match” of simulation program to measured data relies on the input derates – many of which are not known exactly.

Table 3: Hypothetical measured vs. predicted kWh/kWp with different derating factors.

<table>
<thead>
<tr>
<th>Hypothetical measured kWh/kWp</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Program</td>
<td>A</td>
</tr>
<tr>
<td>1) Default derates</td>
<td>1060</td>
</tr>
<tr>
<td>2) 2% more dirt</td>
<td>1040</td>
</tr>
<tr>
<td>3) 2% lower P_{MAX}/P_{Nom}</td>
<td>1020</td>
</tr>
<tr>
<td>4) 2% more shading</td>
<td>1000</td>
</tr>
</tbody>
</table>

Correlation does not imply causation

Claims are often made with yearly tests when a module claimed to perform well under certain weather conditions (e.g. diffuse skies or high temperatures) when tested in a specific climate type (i.e. high diffuse content conditions (e.g. diffuse skies or high temperatures) when module claimed to perform well under certain weather conditions). This indicates that there can’t be large kWh/kWp variations as the modules are quite linear to irradiance and temperature variations site to site.

Apparent measured low light performance depends on irradiance sensor choice

When characterising low light level performance of modules it is essential to consider both the spectral and the angle of incidence differences between the sensor and the PV module.

Figure 13 shows the irradiance values measured by pyranometers vs. corrected ISE sensors on both tilted plane and a 2D tracker for a good irradiance day in April at Oerlikon Solar’s OTF4-AZ. (These traces were corrected to allow for manufacturer’s tolerances by multiplying the irradiance of the ISE sensors to match that seen by the pyranometer only at AM1.5 when blue fraction = 0.52). The lower part of the graph (left y-axis) shows the raw irradiances on the tracker and the tilted plane (and the diffuse horizontal for comparison). At the top and right of the graph are shown the values of $G_{PYR}/G_{ISE, CORR}$ for the two locations. The apparent $G_{PYR}/G_{ISE, CORR}$ on the tilted plane rises away from solar noon due to the combined effects of “angle of incidence” and “solar spectral response” differences between the pyranometer and the ISE sensor. When the sensors are tracked there is a much more linear response just due to the spectrum as the angle of incidence is now 0°.

The vertical line shows when the morning irradiance was around 200W/m² (clear sky, high angle of incidence, spectrum redder than AM1.5). The $G_{PYR}/G_{ISE, TILT}$ is approximately 118% - meaning that under these conditions the Pyranometer reads 18% higher $G_{I}$ than the ISE sensor – this makes a large difference to the “apparent low light level response” under clear sky conditions – it is essential to quote which type of irradiance sensor is used under which weather conditions.
when measuring outdoor low light level coefficients.

Figure 13: Irradiance from a pyranometer vs. corrected @AM1.5 ISE sensor, tilted plane vs. 2D tracked for a good irradiance day in April at Oerlikon Solar’s OTF4-AZ.

Figure 14 replots the data from figure 13 for a c-Si module at OTF4-AZ against irradiance. It shows the raw performance ratio (without spectral or thermal corrections) of two similar c-Si modules in the fixed plane and on the 2D tracker for a clear day in April versus the ISE and Pyranometer scaled so their irradiances match at AM1.5.

The lower plot shows the non temperature corrected performance factor at low light deviating by the 18% error found in figure 13 – meaning that using an ISE reference sensor the PF would appear 18% better than with the pyranometer at 200W/m² under clear skies but high AOI and red rich spectrum.

The upper plot shows very little difference at any light level between the ISE and the Pyranometer on the 2D tracker meaning that most of the deviation is due to the sensor/module angle of incidence differences (corrected out on the 2D tracker) rather than spectrum.

Figure 14: Apparent change in low light behaviour due to sensor choice for a c-Si at Oerlikon Solar’s OTF4_AZ.

Apparent performance at low light level has been shown to depend on whether it’s diffuse sky or clear with high aoi; also it depends on the irradiance sensor used as pyranometers have a different performance at high aoi.

The “Loss Factors Model” has fitted s all technologies tested at two different sites

8 REFERENCES

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Acknowledgements: Oerlikon Solar for outdoor measurement data

7 CONCLUSIONS

Many 3rd party tests only provide kWh/kWp data which is insufficient to differentiate the results – low kWh/kWp may be due to downtime, shading etc., not poor module performance.

Many suggestions have been made for improving the understanding of kWh/kWp measurements